Assessing wet snow avalanche activity using detailed physics based snowpack simulations

N. Wever, C. Vera Valero, and C. Fierz

1School of Architecture, Civil and Environmental Engineering, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, 2WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland

Abstract Water accumulating on microstructural transitions inside a snowpack is often considered a prerequisite for wet snow avalanches. Recent advances in numerical snowpack modeling allow for an explicit simulation of this process. We analyze detailed snowpack simulations driven by meteorological stations in three different climate regimes (Alps, Central Andes, and Pyrenees), with accompanying wet snow avalanche activity observations. Predicting wet snow avalanche activity based on whether modeled water accumulations inside the snowpack locally exceed 5–6% volumetric liquid water content is providing a higher prediction skill than using thresholds for daily mean air temperature, or the daily sum of the positive snow energy balance. Additionally, the depth of the maximum water accumulation in the simulations showed a significant correlation with observed avalanche size. Direct output from detailed snow cover models thereby is able to provide a better regional assessment of dangerous slope aspects and potential avalanche size than traditional methods.

1. Introduction

In mountainous regions, wet snow avalanches pose a serious threat to society and infrastructure. The wetness of the released snow contributes to dense flows, and lubrication at the base of the flow can occasionally cause long runout distances [Naaim et al., 2013]. There is an increasing demand for forecasting wet snow avalanche activity [e.g., Zischg et al., 2005; Mitterer et al., 2013]. Lazar and Williams [2008] have shown that global warming may cause a shift of wet snow avalanche activity into the operational ski season of ski resorts. Also, the proportion of wet snow avalanches as compared to dry snow avalanches may increase in the future [Martin et al., 2001; Pielmeier et al., 2013; Castebrunet et al., 2014], although regionally, historical trends were found to be opposite [Bellaire et al., 2016].

Most studies addressing the predictability of wet snow avalanches use statistical methods to relate meteorological conditions or the snowpack energy balance to wet snow avalanche activity [Romig et al., 2004; Zischg et al., 2005; Jomelli et al., 2007; Baggi and Schweizer, 2009; Peitzsch et al., 2012; Mitterer and Schweizer, 2013; Helbig et al., 2015]. Although a significant positive energy balance of the snowpack is often required to predict wet snow avalanche activity, calculating the snow energy balance only is often not sufficient. The thermal state of the snowpack is also important, i.e., wetting of an initially below freezing snowpack is more critical for snowpack stability than additional melt occurring in a ripe snowpack [Armstrong, 1976; Durand et al., 1999; Techel et al., 2011; Mitterer and Schweizer, 2013].

Ultimately, the wet snow avalanche formation process is governed by liquid water flow processes in snow. A prominent characteristic of water flow in snow is ponding at capillary barriers caused by transitions in grain size, grain shape, or density [Wakahama, 1975; Marsh and Woo, 1984; Conway and Benedict, 1994; Waldmeyer et al., 2004]. The water ponding process is generally considered to be an important factor in wet snow avalanche formation [e.g., Kattelmann, 1984; Fierz and Föhn, 1994; Mitterer et al., 2011; Takeuchi and Hiroshima, 2013], and the presence of capillary barriers has been statistically linked to wet snow avalanche activity [Baggi and Schweizer, 2009]. Based on field experiments, it is generally considered that snow strength is strongly reduced once volumetric liquid water content (LWC) exceeds 5–7% [Brun and Rey, 1987; Bhutiyani, 1996; Yamanoi and Endo, 2002; Ito et al., 2012]. As the typical LWC of snow in the absence of gradients in capillary suction is below this value [Coléou and Lesaffre, 1998; Heilig et al., 2015], ponding inside the snow cover seems to be an important prerequisite to reduce the stability of a wet snowpack. In recent laboratory experiments, LWC in layers adjacent to capillary barriers was found to peak around 33% [Avanzi et al., 2015].
Recent improvements in the simulation of liquid water flow in the numerical SNOWPACK model [Bartelt and Lehning, 2002; Lehning et al., 2002a, 2002b] by using Richards equation [Hirashima et al., 2010; Wever et al., 2014] allow for the direct simulation of ponding conditions inside the snowpack [Hirashima et al., 2014; Wever et al., 2015; Avanzi et al., 2015]. This study aims to investigate whether the occurrence of ponding at layer interfaces inside the snowpack can be related to wet snow avalanche activity. An advantage of using physics based models is that they ideally do not require site-specific calibration. This is tested for by analyzing data from three different climate regimes: the Swiss Alps, the Spanish Pyrenees, and the Chilean Central Andes.

2. Data and Methods
2.1. Meteorological Forcing Data and Simulation Setup
Meteorological forcing data to drive the SNOWPACK model was collected from three measurement sites, located in three different mountain ranges with varying climatological regimes. The Weissfluhjoch (WFJ) measurement site is located at 2540 m above sea level (asl) in the Swiss Alps (46.83°N, 9.81°E) and is equipped with high-quality instruments [WSL Institute for Snow and Avalanche Research SLF, 2015]. We consider here the period October 2001 to July 2015, corresponding to the period for which consistent avalanche activity data are available. The Codelco-Andina mine is located 100 km northeast of Santiago in the Chilean Central Andes. We use data from the automatic weather station Laguna Angela (LAG, 33.03°S, 70.28°W, 3550 m asl), operated by the mine, for the period January 2010 to December 2015. Finally, the avalanche warning service of Val d’Aran in the Spanish Pyrenees operates the Comalada (COM) meteorological station (42.71°N, 0.94°E, 2075 m asl), from which we use data between October 2012 and June 2015. At all three stations, air temperature, relative humidity, wind speed, incoming shortwave radiation, and snow height are measured. At WFJ and LAG, additionally reflected shortwave radiation is measured. For WFJ, this allows us to drive the SNOWPACK model with measured snow albedo. The absence of ventilation or heating of the incoming shortwave radiation sensor at LAG to prevent riming or snow piling up made us decide to use the reflected shortwave radiation sensor in combination with parametrized albedo to determine net shortwave radiation. At COM, net shortwave radiation is determined using the incoming shortwave radiation sensor and the parametrized albedo. Furthermore, in contrast to the WFJ site, at LAG and COM the sensors for air temperature and relative humidity are not ventilated, and there are no incoming longwave radiation measurements. For these two stations, the incoming longwave radiation is parametrized using air temperature, relative humidity, and cloudiness [Omstedt, 1990], where cloudiness is estimated from measured shortwave radiation [Bavay and Egger, 2014]. WFJ is additionally equipped with a heated rain gauge, enabling also an estimation of the occurrence of rainfall events for this site.

The physics based snow cover model SNOWPACK was used to simulate the temporal evolution of the snowpack at the meteorological stations. Liquid water flow in snow was solved using Richards equation (RE), which was found to improve several aspects (e.g., percolation time) of the simulation of liquid water flow in snow [Wever et al., 2014, 2015]. Furthermore, the simulations with RE reproduced accumulations of liquid water at microstructural transitions inside the snowpack [Wever et al., 2015]. These arise from variable water retention curves, currently parameterized depending on grain size and density [Yamaguchi et al., 2012] and gradients in hydraulic conductivity. The layer thickness of snowpack layers in the SNOWPACK model is variable due to variations in snow settling but typically is around 2 cm. Here the hydraulic conductivity at the interface nodes is calculated with the geometric mean [Wever et al., 2015], which is able to reproduce the LWC values of around 33% at microstructural transitions inside the snowpack, as observed in laboratory experiments [Avanzi et al., 2015].

As the stations are located on flat sites, they cannot be regarded as representative for avalanche release zones in steep slopes. For this reason, four main virtual slopes [Lehning and Fierz, 2008] were used with a north, east, south, and west aspect and a slope angle of 35° (similar to Mitterer and Schweizer [2013]). For WFJ, four additional virtual slopes (northeast, southeast, southwest, and northwest) were used for the direct comparison with aspects used in avalanche activity reports. Direct shortwave radiation as measured at the flat measurement site was projected on those virtual slopes. Snow height measurements were used to determine snowfall at the flat field, which was subsequently projected on the virtual slopes. The analysis is limited to the period with a snowpack at the flat measurement site, as otherwise, the meteorological measurements are not representative for slopes that are still snow covered.
2.2. Wet Snow Avalanche Activity Data

Wet snow avalanche activity within a maximum distance of approximately 25 km from WFJ has been derived from daily reports by trained observers for the period October 2001 to July 2015. Avalanches are considered wet when the snow in the release area is wet. The reports may concern a single avalanche but more often summarize daily activity by reporting the number of avalanches, subdivided into the five Canadian size classes [McClung and Schaerer, 2006]. Additionally, the lowest and highest release elevation are provided in steps of 200 m when reporting multiple avalanches, and a single release elevation when a single avalanche is reported. Observers also indicate the slope aspects in which wet snow avalanche activity is observed, subdivided into eight aspects. To match the avalanche activity with the simulations for the WFJ measurement site, we selected avalanche reports of wet snow avalanches with either the lowest or highest reported release elevation between 2200 and 2800 m asl. This selection procedure results in a 14 season total of 213 avalanche days and 2979 days with no wet avalanches reported. When analyzing individual slope aspects, we require both the lowest and the highest release elevation to lie in this elevation band. An avalanche activity index (AAI) is then computed by weighting the number and size of the reported avalanches, using weights 0.01, 0.1, 1.0, and 10.0 for each very small, small, medium, and large avalanches, respectively [Schweizer et al., 1998].

The dedicated avalanche service at the Codelco-Andina mine in Chile monitors avalanche activity in an area of about 70 km², particularly for avalanche paths that may potentially pose a threat to the infrastructure or the access roads of the mine. Small avalanches in nonthreatening slopes are not necessarily getting reported. Totaled over six seasons (2010–2015), the data set consists of 943 nonavalanche days and 50 avalanche days. Due to the limited number of observed avalanches, we did not apply an additional criterion for release elevation.

The avalanche warning service of Val d’Aran in Spain also records avalanche activity within approximately 20 km distance from the COM measurement site by mapping the avalanche paths and documenting the type of avalanche. Using the ASTER Global Digital Elevation Model [METI/NASA/USGS, 2009], the elevational range of occurred wet snow avalanches was determined. The upper one third of the avalanche outline was considered the release area, and only avalanches where the middle of the release area was between 1675 and 2475 m asl were considered. For the three winter seasons in the data set (2013–2015), this selection procedure results in 496 nonavalanche days and 28 avalanche days.

2.3. Methods

To synthesize useful information from the numerical snowpack simulations, we analyze the daily sum of positive surface energy balance of the snowpack, determined at each model time step of 15 min (similar to Mitterer and Schweizer [2013]) as well as the highest LWC found in any of the snowpack layers in the simulations (henceforth denoted as maximum local LWC). From the meteorological measurements, the daily mean air temperature was taken into consideration as an example of a prediction method that does not require the use of a snowpack model. We consider the strategy of predicting wet snow avalanche days based on the exceedance of a threshold in these three variables in one or more of the four virtual north, east, south, and west slopes.

The correspondence of predicted and observed wet snow avalanche activity is investigated using dichotomous contingency tables, where both the observations and the simulations can indicate either a wet snow avalanche day or a non-wet snow avalanche day. The Hanssen-Kuipers skill score (HKS) [Hanssen and Kuipers, 1965] is considered a suitable metric to judge overall performance of the dichotomous predictions, without requiring equalizing the number of events and nonevents [Woodcock, 1976]. We also calculate the probability of detection (POD), defined as the number of correctly predicted avalanche days divided by the total number of observed avalanche days; the probability of null events (PON), defined as the number of correctly predicted nonavalanche days divided by the number of observed nonavalanche days; the false alarm ratio (FAR), defined as the number of days predicted as an avalanche day, which was not observed as one, divided by the total number of predicted avalanche days; and the accuracy (ACC), defined as the total number of correctly predicted avalanche and nonavalanche days divided by the total number of days [Doswell et al., 1990].

We determined the prediction thresholds for avalanche or nonavalanche days for each of the variables separately as those that provide the highest HKS. This calibration is performed with the seven even years from WFJ, using the other seven uneven years for validation. Further validation is performed by a comparison with the simulations and wet snow avalanche data from the Central Andes and Pyrenees. The expression for the
3. Results and Discussion

Figure 1 displays the evolution of the snow height, daily sum of positive energy balance, maximum local LWC and wet snow avalanche activity during the 7 calibration snow seasons at WFJ. The snow height is the average value over all main four slope aspects, whereas the other variables are the daily maximum values found in either one of those slope aspects. The snow season at WFJ typically consists of a cold winter period, where the snow melt is concentrated in south facing (sunny) slopes, followed by a melt period in spring with snow melt occurring in all slope aspects. The peak in wet snow avalanche activity is often found shortly before or after the maximum snow height is reached and is accompanied by peaks in both the daily sum of positive energy balance as well as the maximum local LWC inside the snowpack. However, while the energy balance increases toward the end of the melt season, driven by an increase in air temperature and incoming solar radiation toward the summer season, avalanche activity is declining. In contrast, the maximum local LWC found inside the snowpack is peaking during periods of wet snow avalanche activity and declining afterwards, a pattern which visually seems to be in closer correspondence with the avalanche observations.

Peaks in maximum local LWC in the simulations often coincide with the first wetting as a result of the combined effect of ponding on capillary barriers and a strong gradient in hydraulic conductivity over the barrier. Later in the melt season, when the snowpack is also moist below the capillary barrier, the gradient in hydraulic conductivity is reduced, weakening the strength of the capillary barrier. These model simulations thereby seems to be congruent with the notion that the first wetting of the snowpack is particularly dangerous [Durand et al., 1999; Techel et al., 2011]. A few peaks in maximum local LWC do not correspond to periods with wet snow avalanche activity (for example in 2002 and 2006), which seems to particularly occur in south facing slopes when the maximum local LWC content is found close to the snow surface (see Figure 1).

In Figure 2, the distributions of daily mean air temperature, daily sum of positive energy balance and the maximum local LWC are shown for WFJ, LAG, and COM, separated into days on which wet snow avalanches
Figure 2. Box and whisker plot showing the distribution of daily mean air temperature (TA), highest daily sum of positive energy balance (EB), and highest daily maximum local LWC in one of the four simulated virtual slopes separated into avalanche days and nonavalanche days. Boxes represent interquartile ranges (25th to 75th percentiles), thick horizontal bars in each box denote the median (50th percentile), and whiskers (vertical lines and thin horizontal bars) represent the highest and lowest value within 1.5 times the interquartile range above the upper or below the lower quartile, respectively. Notches are drawn at \( \pm 1.58 \) times the interquartile range divided by the square root of the number of data points. Outliers are not shown.

were observed and days without reports of wet snow avalanche activity. The Kolmogorov-Smirnov test showed that for all three variables, the distributions differ significantly \((p < 0.05)\) between avalanche and nonavalanche days for WFJ and LAG. For COM, only the maximum local LWC distribution differs significantly between avalanche and nonavalanche days. For all three sites, the Kolmogorov-Smirnov test statistic is larger for the maximum local LWC than for the daily sum of positive energy balance or the daily mean air temperature. The Mann-Whitney-Wilcoxon test yields similar results, also indicating that for COM, only the median of maximum local LWC is significantly different \((p < 0.05)\) on avalanche and nonavalanche days, whereas for WFJ and LAG all three variables have a significantly different median \((p < 0.05)\). The test statistic is again highest for maximum local LWC, indicating that of the three variables studied here, the maximum local LWC seems most suited for separating avalanche from nonavalanche days.

For the area surrounding WFJ, the long and detailed data set enables a separation into individual slope aspects. Figure 3 shows the distributions of the daily sum of positive energy balance and the maximum local LWC as a function of slope aspect, separated into days with and without wet snow avalanche activity reports for the particular slope aspect. A clear dependence of the daily sum of positive energy balance with slope aspect is found for days with observed wet snow avalanche activity. This can be attributed to the aspect dependence of incoming shortwave radiation. In contrast, the median of the maximum local LWC varies between 5 and 7%, and only a weak dependence with slope aspect is present.

We now consider the prediction strategy for wet snow avalanche activity based on whether the chosen prognostic variables exceed a certain threshold. An avalanche day is predicted when the daily mean air temperature exceeds \(-3.9\,^\circ\text{C}\), the daily sum of positive energy balance exceeds 2.5 mm water equivalent (mm w.e.) or the maximum local LWC exceeds 6.3% in one or more of the four main virtual slope aspects. These thresholds were determined to provide the highest HKS for the seven calibration years from WFJ and were subsequently verified using the other 7 years from WFJ as well as the full data set for LAG and COM. For the validation data sets, Figure 4 shows five characterizing statistics (POD, PON, FAR, ACC, and HKS) describing the quality of this prediction method. Using the maximum local LWC provides the highest HKS for all three sites WFJ \((0.46(\pm0.05))\), LAG \((0.38(\pm0.07))\), and COM \((0.29(\pm0.08))\), as well as the highest ACC. For all sites, the daily sum of positive energy balance is showing larger skill \((\text{HKS} \text{ of } 0.38(\pm0.05), 0.19(\pm0.07) \text{ and } 0.06(\pm0.09) \text{ for WFJ, LAG, and COM, respectively})\) than using the daily mean air temperature \((0.37(\pm0.05), 0.12(\pm0.07) \text{ and } 0.04(\pm0.09) \text{ for WFJ, LAG, and COM, respectively})\), although differences between both variables are smaller than the difference with maximum local LWC. The fact that both the calibration and validation data set were
Figure 3. Box and whisker plot showing the distribution of the daily sum of positive energy balance (EB) and daily maximum local LWC per slope aspect and separated into avalanche days and nonavalanche days. The number in brackets below the x axis labels denote the number of days in the respective distributions. Boxes represent interquartile ranges (25th to 75th percentiles), thick horizontal bars in each box denote the median (50th percentile), and whiskers (vertical lines and thin horizontal bars) represent the highest and lowest value within 1.5 times the interquartile range above the upper or below the lower quartile, respectively. Notches are drawn at $\pm 1.58$ times the interquartile range divided by the square root of the number of data points. Outliers are not shown. The dashed horizontal lines indicate the thresholds to distinguish between avalanche and nonavalanche days, determined by calibration, for daily sum of positive EB (red) and maximum local LWC (blue).

The proportion of correctly predicted avalanche days (POD) is lower when using the maximum local LWC, whereas this variable is generally better in predicting the abundant nonavalanche days (i.e., a higher PON).

Figure 4. Probability of detection (POD), probability of null events (PON), false alarm ratio (FAR), accuracy (ACC), and Hanssen-Kuipers skill score (HKS) for predicting wet snow avalanche days based on the exceedance of a threshold for the following: daily mean air temperature, daily sum of positive energy balance, and the daily maximum local LWC, for WFJ, Switzerland (blue); LAG, Chile (red); and COM, Spain (green). Error bars extent over $\pm 1$ standard deviation for the HKS.
Figure 5. Box and whisker plot showing the distribution of the depth below the snow surface, perpendicular to the slope, where (a) the maximum LWC is found and (b) the total snow thickness (i.e., perpendicular to the slope), for the maximum avalanche size reported, based on the WFJ data set. Boxes represent interquartile ranges (25th to 75th percentiles), thick horizontal bars in each box denote the median (50th percentile), its value shown directly above the bar. Whiskers (vertical lines and thin horizontal bars) represent the highest and lowest value within 1.5 times the interquartile range above the upper or below the lower quartile, respectively. Notches are drawn at $\pm 1.58$ times the interquartile range divided by the square root of the number of data points. Outliers are not shown.

Therefore, the overall accuracy of all predictions (i.e., ACC) using maximum local LWC is higher than those using the daily sum of positive energy balance or the daily mean air temperature, even for individual slopes (not shown). However, the FAR is relatively high in all cases for all variables. Thus, although avalanche reports are probably not providing a complete record of all avalanche activity in the region, water accumulating on capillary barriers inside the snow cover is likely not a sufficient condition for a release. Long-term exposure of a snowpack to wet conditions and associated wet snow metamorphism may stabilize the snowpack, while capillary barriers or crusts may continue causing ponding. Furthermore, the number of avalanche paths in a region is limited, and multiple avalanches in the same season and path are less likely, reducing the number of potential wet snow avalanche days.

The size of an avalanche is, among many factors (e.g., release area and the topology of the avalanche path), partly determined by release depth. As the capillary barrier at which liquid water is accumulating can be considered the potential failure layer for a wet snow avalanche, a relationship of this depth with avalanche size is expected. Figure 5a shows the distribution of the depth below the snow surface where the maximum local LWC is found (ponding depth) on days and in slope aspects where avalanches were reported as a function of the largest observed avalanche size for the WFJ data set. An increasing trend of the median in simulated ponding depth with observed avalanche size is present, ranging from 34 cm for very small avalanches to 70 cm for large avalanches. The Kendall Tau-b nonparametric rank correlation test showed that the correlation between ponding depth and avalanche size is statistically significant with $\tau_b = -0.17$ ($p < 0.05$). An other important factor determining avalanche size is the total snow depth [e.g., Eckert et al., 2010]. Figure 5b shows that a relationship between avalanche size and simulated snow depth in the corresponding slope aspect is also present in the WFJ data set, with $\tau_b = 0.13$ ($p < 0.05$). Thus, the correlation of avalanche size with ponding depth is stronger but of similar order of magnitude as with total snow depth. Fracture depth and snow cover properties in the release zone may serve as valuable input for avalanche dynamics models [e.g., Vera Valero et al., 2015].

4. Conclusions

Simulated water accumulations of more than approximately 5–6% LWC at capillary barriers formed by microstructural transitions inside the snowpack could be related to wet snow avalanche activity. A higher prediction skill in terms of HKS was achieved than using commonly used parameters like daily mean air temperature or the daily sum of positive energy balance. The prediction skill also holds for individual slope aspects and was verified for three climatological regimes. Additionally, a correlation was found between the depth inside the snowpack where liquid water is accumulating, which we consider the potential failure layer, with the observed avalanche size. This information is crucial to estimate runout distances and the potential
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harm to infrastructure and society. Although many more factors determine the eventual avalanche risks, we demonstrated that physics based snowpack models can nowadays provide useful information for assessing regional wet snow avalanche risks, specified for individual slope aspects and altitude bands. Furthermore, the information of the snow cover state from the simulations can be used to drive avalanche dynamics models.

As we only focused on one simple physical quantity to relate water flow to wet snow avalanche activity, we interpret our results as a first step that seems to indicate a large potential of physics based snowpack models for wet snow avalanche forecasting. If future research focuses on improving the representation of the wet snow avalanche formation process in snowpack models, particularly regarding mechanical properties of wet snow, as well as acquiring representative meteorological forcing conditions for avalanche slopes, we anticipate physics based snow cover models to further improve their skill for assessing wet snow avalanche risks.

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References


METI/NASA/USGS (2009), ASTER Global DEM Validation Summary Report, METI/ERSDAC, NASA/LPDAAC, USGS/EROS.


